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Research Department Report

SATELLITE BROADCASTING:

Requirements for the receiving antenna

J.H. Stott, M.A.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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Summary

The receiving antenna plays a significant part in the reception of television signals broadcast from a satellite in so-called Direct Broadcasting by Satellite (DBS). The performance of the antenna must be sufficiently good to ensure that signals are received without suffering adverse effects of noise or interference. A hypothetical receiver specification was used during the planning of satellite broadcasting at the World Administrative Radio Conference in 1977 (WARC-77), but while this is in general ***sufficient*** *it may not always be* ***necessary****. Furthermore, the different trade-offs involved in novel antenna designs (including flat-plate types) may mean that the same result can most effectively be obtained with a very different specification.*

This Report explains the various requirements and gives examples of different ways to satisfy them, including some discussion of the consequences of incomplete or lower-power use of the WARC-77 allocations. It provides a useful background to related Research Reports which describe work on flat-plate antennas.

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M.E.B. Moffat

Head of Research Department

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1. INTRODUCTION

Direct Broadcasting by Satellite (DBS) of television programmes should shortly be a reality in Europe. A DBS service is already being provided in Japan[1], while Australia has a 'quasi-DBS' service[2] used to distribute programmes to small communities. Communications satellites are widely used to distribute programmes for cable systems in both Europe and the United States, and these too are received directly by some individuals. 'True' DBS in Europe will use the frequency band 11.7-12.5 GHz, according to the Plan[3] drawn up at a World Administrative Radio Conference in 1977 (hereafter referred to as the WARC-77 Plan). Programme distribution using communications satellites takes place in bands allocated to the Fixed-Satellite Service, principally at 4 and 11 GHz. Other bands at higher frequencies (around 23, 42 and 84 GHz) are also allocated to satellite broadcasting, and may be used at a later date, perhaps for delivery of High Definition Television.

A significant link in the chain from the broadcaster to the viewer is the receiving antenna. It is one of the more visible parts of the viewer's investment in receiving equipment. Its cost and ease of installation will influence the take-up of a new service. Its performance, together with that of the associated front end, has a major influence on the quality of the received pictures and sound. Technically, we may consider that the antenna serves two purposes. It must collect sufficient energy from the wanted signal to overcome the effects of *noise*, while adequately rejecting unwanted signals which would cause *interference*. Furthermore, the level of performance required will depend on the environment in which reception is required — for example, the climatic conditions will be shown to influence both noise and interference.

The specification of a DBS antenna is thus not a simple task since there is a trade-off between the quality of the received signal and the size, expense and location of the antenna. The full details of the compromise are often not fully appreciated.

This Report considers the part the receiving antenna plays in a DBS system and shows how an appropriate specification for it can be arrived at for particular requirements. It should be noted that the discussion is limited to the scenario of reception at fixed points — the typical television installation in the home.

Two main types of antenna are considered for the DBS application. One is the 'dish' antenna, with a reflector, commonly a paraboloid, together with a feed arrangement, of which many variations are found. The design and manufacture of dish antennas is now a fairly well-known art, so that good performance can be obtained at reasonable cost. Various potential disadvantages stem from the bulky nature of dish antennas: they are obtrusive in appearance and may be difficult (or at least expensive) to mount sufficiently securely to withstand wind loading. These difficulties are avoided by the alternative, a 'flat-plate' antenna which could be mounted directly on an appropriate wall. This type is not, as yet, so well developed as the dish antenna, but it is under active study.

The work in this Report was undertaken in order to assist the development of flat-plate antennas, as reported in detail in companion Reports[4,5,6,7].

2. THE ASSUMPTIONS MADE ABOUT THE RECEIVING ANTENNA IN INTERNATIONAL PLANNING

2.1 The use of a hypothetical specification in planning

As already noted, a receiving antenna serves two purposes: to gather sufficient wanted-signal energy to overcome noise, while rejecting unwanted signals which would cause interference. Similarly, the process of international planning of a broadcast service seeks to ensure that viewers or listeners can receive signals of sufficient strength and sufficiently free of interference, provided that they use equipment of a certain minimum standard and are situated within the intended service area. The 'minimum standard' of equipment must be defined at an early stage in planning, and will include a specification of the receiving-antenna characteristics.

It is important to note that the equipment specification used in broadcast-service planning is hypothetical. It need not correspond to the performance of any physically-existing receiver and it is not in any way mandatory on the viewer or listener that his equipment meets the specification. If the planning has been successful then the use of equipment of the hypothetical standard will result in reception, with at least the planned standard of quality, at any point within the service area, provided that all transmissions are made in accordance with the plan. Nevertheless, it may be possible to use equipment of a lower standard in parts of the service area and still obtain the planned quality or better. The viewer or listener is always free to use equipment of lower standards and accept any reduction in quality that results; equally he may use equipment of higher standards and in the right circumstances this may give better quality than planned, or permit reception beyond the intended service area.

2.2 The parameters commonly specified

DBS can be used in two ways: 'direct reception', in which each domestic receiving installation has its own antenna receiving signals from the satellite; and 'community reception', where a single antenna, usually of larger size, receives the signals which are then fed to several homes by, for example, a cable system. Higher standards are usually proposed for a community-reception installation in order to allow for possible degradation of the signal during its distribution to individual homes. International planning may make appropriate provisions for both types of reception; however, this Report is mainly concerned with individual reception.

The problem of ensuring that the antenna gathers sufficient wanted-signal energy to overcome noise and thus achieve an adequate signal-to-noise ratio is the one which generally attracts the greatest attention. This aspect of the performance is usually characterised by the *receiver figure of merit, G/T*. This parameter will be described in more detail in a later section, but in short it is a way of assessing the receiver which takes into account the fact that the same 'clear-sky' performance could be achieved with a large antenna and a noisy front end as with a small antenna coupled to a better, quieter front end. We shall see later that this figure of merit is not strictly constant under all circumstances, and should therefore be used with care; nonetheless it is a very useful tool which is frequently applied.

The ability of the antenna to discriminate against interference plays a vital part in the construction of a plan for broadcasting, since with limited spectrum available it is mutual interference between services which ultimately sets the limit to what can be provided. However, this aspect of antenna performance tends to be somewhat neglected once planning is completed. The usual approach in planning is to adopt templates for the co-polar and cross-polar radiation patterns. 'Co-polar' and 'cross-polar' are of course with respect to the specified polarisation of the wanted service. Note that the use of circular polarisation was generally assumed* at WARC-77.

3. NOISE

3.1 The basis of link budgets

A link budget is simply an orderly presentation of all the factors which affect a signal in its passage from the transmitter to its destination. Applied to the present subject of broadcasting it relates the received signal-to-noise ratio (and hence the quality of the picture and sound) to the transmitter power and the many parameters of the link between them. The analogy with financial budgets implied by the name is apt because the use of decibel representation means that most of the calculation can be presented as a table of quantities which are added or subtracted.

3.1.1 The basic link budget

The basic link-budget relationship can be expressed as follows†, although we shall see later that many refinements can be made which permit a more detailed appreciation of the problem.

$$(C/N) = E_{\mathrm{TX}} - L_{\mathrm{SPREADING}} - L_{\mathrm{SLANT\text{-}PATH}} + (G/T) + A_{\mathrm{ISOTROPIC}} - B_{\mathrm{NOISE}} - K,$$

where:

(C/N) is the *carrier-to-noise ratio* in dB, measured in the receiver noise bandwidth;

E_{TX} is the *effective isotropically radiated power* (EIRP) of the satellite in the direction of the receiver, in dBW;

$L_{\mathrm{SPREADING}}$ is the *spreading loss* in dBm^2, equal to $10 \log_{10} (4\pi r^2)$, where r is the distance in metres from the satellite to the receiver; for paths from the geostationary orbit to the Earth's surface its value is approximately 163 dBm^2;

$L_{\mathrm{SLANT\text{-}PATH}}$ is the *excess slant-path loss* in dB, comprising attenuation caused by atmospheric gaseous absorption and attenuation caused by *hydrometeors* (rain, ice, snow, etc.);

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* Circular polarisation is specified for all the beams of the WARC-77 Plan for Regions 1 and 3 (Europe, Africa, Asia, Australia and most of the Pacific). However, the Administration of Iran reserved the right to use linear polarisation instead. Circular polarisation was also assumed at the Regional Administrative Radio Conference of 1983 (RARC-83) which drew up the Plan for 12 GHz satellite broadcasting in Region 2 (the Americas).

† There is a need to distinguish quantities expressed in dB from those expressed in the normal linear way; this leads us to adopt the convention that A stands for the decibel representation of quantity a, i.e. $A = 10 \log_{10} a$. One distortion of this convention will be made for the sake of familiarity: certain ratios, for example the carrier-to-noise ratio, should strictly be written as c/n (the pure ratio) and C-N (the ratio expressed in dB). Although 'C-N' is correct and consistent, it is totally alien to normal usage so '(C/N)' will be taken to mean 'the value, expressed in dB, of the ratio c/n', i.e. $(C/N) = 10 \log_{10} (c/n)$. This dispensation need only be applied to a few standard ratios, including C/N, S/N, and G/T.

(G/T) is the *receiver figure of merit*, in dB/K, calculated as $10 \log_{10} (g/t)$, where g is the net gain of the receiving antenna in the direction of the satellite, relative to an isotropic radiator, and t is the net system noise temperature; it will be shown later that (G/T) of a given receiver is not invariant;

$A_{\text{ISOTROPIC}}$ is the *equivalent effective area of an isotropic radiator*, in dBm^2, which when added to the receiving antenna gain in dBi gives the effective area of the actual receiving antenna; it is equal to $10 \log_{10} (\lambda^2/4\pi)$, where λ is the wavelength in metres;

B_{NOISE} is the receiver *noise bandwidth*, expressed in dBHz;

K is the *Boltzmann constant*, equal to 228.6 dBWHz^{-1} K^{-1}.

The quantity $\{E_{\text{TX}} - L_{\text{SPREADING}} - L_{\text{SLANT-PATH}}\}$ is the received *power flux density*, expressed in dBW/m^2. The satellite EIRP E_{TX} is obtained by adding the transmitting antenna gain in the direction in question, G_{TX} (dBi), to the net transmitter power supplied to the antenna, P_{TX} (dBW).

3.1.2 The receiver figure of merit (G/T)

The receiver figure of merit (G/T) takes into account the effects of various losses on receiver performance. These effects comprise both a reduction in the net gain and also an increase in the overall receive-system noise temperature. It is possible to identify many types of loss or inefficiency in the antenna/ receiver combination, but these can be grouped together to give the following simplified presentation[3,8a]:

$$(g/t)_{\text{NET}} = \frac{\alpha\beta g_{\text{r}}}{\{\alpha t_{\text{ANT}} + (1-\alpha)\, t_0 + (n-1)\, t_0\}}$$

where:

α = the total *dissipative* losses (expressed as a numerical power ratio), caused for example by feed attenuation;

β = the total *non-dissipative* losses due to pointing error, polarisation effects, equipment ageing, etc. (expressed as a numerical power ratio);

g_{r} = the effective gain of the receiving antenna, expressed as a numerical power ratio and taking account of illumination method and efficiency;

t_{ANT} = the effective temperature of the antenna (K);

t_0 = the reference temperature = 290 K*;

n = the overall noise factor of the receiver, expressed as a numerical power ratio. (The commonly-quoted *noise figure* N dB = $10 \log_{10} n$).

The denominator of the expression is the *overall receive-system noise temperature* t_{SYSTEM}. It is affected by the receiver noise figure, dissipative losses and also by the antenna temperature t_{ANT} which is itself a function of the slant-path losses, as explained in the Appendix. The numerator includes all losses, dissipative and non-dissipative, except slant-path losses.

3.2 The effects of atmospheric attenuation

As mentioned in the previous section, the signal from the satellite suffers excess attenuation, over and above that which would occur in free-space propagation, while travelling along the slant path through the atmosphere. This excess attenuation has two components. One, caused by gaseous absorption, is always present; it is due primarily to atmospheric water vapour and oxygen. The second component is caused by hydrometeors: rain, sleet, snow, ice and hail. Modelling of both these attenuation mechanisms, so that their effects may be predicted, is under constant study worldwide. One international forum for the dissemination of the results is Study Group 5 of the CCIR (International Radio Consultative Committee).

Before examining the models in any detail, one rough-and-ready generalisation may be made: the higher the angle of elevation, the shorter the slant path through the atmosphere and thus the lesser the attenuation, other things being equal. (This is not strictly true for localised rain storms).

As already noted, the excess slant-path loss affects the link budget in two ways; as well as the obvious effect of signal attenuation it also affects the noise temperature of the receiver and thus its G/T.

3.2.1 Gaseous absorption

This does not pose a significant problem at 12 GHz.

The specific attenuation (expressed in dB/km) depends on the frequency and the partial pressures of the various atmospheric constituents. There are specific frequency bands in which the absorption caused by particular molecules is particularly significant, for example around 22.3 GHz for water vapour and around 60 GHz for oxygen. The partial pressure of oxygen varies with height, whereas that of water vapour additionally varies significantly with location and time. To evaluate the total slant-path attenuation the specific attenuation must be integrated along the path. Fig. 1, adapted from CCIR Report 719-2[9] which discusses absorption in detail, shows how the total attenuation on a zenithal (i.e. vertical) path varies with frequency. The corresponding attenuation on a slant path having elevation $\delta > 90°$ may be estimated by multiplying by cosec δ, provided δ is not too small — say, $\delta > 10°$. More accurate formulae accounting for the curved nature of the path due to atmospheric refraction are given in Report 719.

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* Strictly the term $(1-\alpha)\, t_0$ should use the physical temperature of the feed (or whatever is causing the loss) rather than t_0, which is a reference temperature. The use of t_0 in the term $(n-1)\, t_0$ is correct by definition of n.

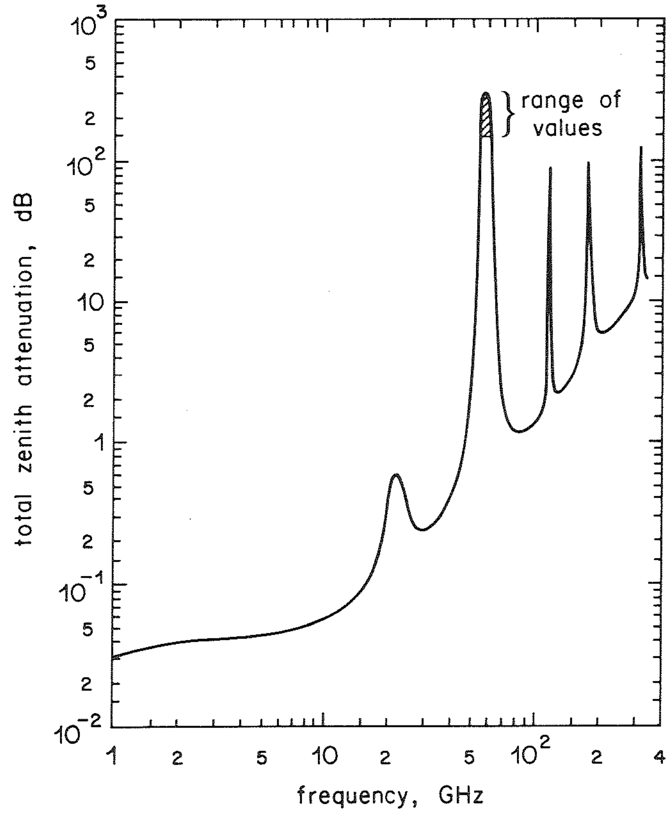

Fig. 1 - Total zenith attenuation by atmospheric gases, after CCIR Report 719-2.

For ground-level conditions:

Pressure: 1 atm
Temperature: 20°C
Water vapour: 7.5 g/m^3

We may conclude that gaseous absorption is not a serious problem to satellite broadcasting at the frequencies presently considered, remembering that for this purpose it is desirable to avoid very low elevation angles anyway*. Fig. 1 shows that with typical humidity the zenith attenuation at 12 GHz is about 0.07 dB, corresponding to about 0.2 dB for a path having 20° elevation. At the peak of the 22.3 GHz absorption band, the corresponding figures are 0.6 dB and 1.75 dB respectively. We shall see shortly that attenuation caused by rain, etc., is generally more significant, although the above-quoted 'typical' figures may be increased during times of very high rainfall because of the concomitant rise in humidity.

3.2.2 Attenuation caused by hydrometeors

A method for predicting attenuation on a slant path due to hydrometeors is given in CCIR Report 564[10], using data from Report 563[11]. Other models exist, notably one developed by the European Space Agency (ESA) for the European region[12]. The results are statistical in nature, in that what is calculated is the attenuation A_p dB which is exceeded for p % of the average year. The results depend on the local climate (often described in terms of 'rain zones'), elevation and latitude, and to a lesser extent on polarisation. Fig. 2. shows how the attenuation A_p varies with p at 12 GHz, for paths from three locations in the UK to a satellite at 31°W (the orbit position allocated to the UK by WARC-77), according to the model and data of CCIR Reports 564-3 and 563-3.

3.2.3 Consequential *G/T* variation

If the signal from the satellite were to suffer no attenuation at all in passing through the Earth's atmosphere, then the only contribution to the noise temperature of an ideal antenna (having no losses, no sidelobes and a very narrow main beam) would be the cosmic background temperature, about 3 K — unless the antenna were 'looking' at another noisy body such as the sun†. Practical antennas will have additional contributions because of feed losses and also because sidelobes (and, for very small elevation angles, even part of the mainlobe) will 'see' the ground.

* At very low elevation angles it will be hard for the average householder to find an unshadowed site for the receiving antenna; furthermore there is a greater risk of picking up man-made interference of terrestrial origin and noise radiated from the earth, which in space communication terms has a high noise temperature.

† The sun is a significant source of radio-frequency noise and gives rise to the so-called *sun-blinding* effect. Significant reduction of the received *C/N* can occur at times of *conjunction* of the sun and the satellite, i.e when the sun appears to be situated behind the satellite being received. This occurs at certain times of day for a few successive days during two periods in each year. On the worst day the effect lasts about 10 minutes, with an annual total of about one hour.

The effect is to increase the antenna noise temperature t_{ANT} (see Appendix) by an amount t_{SUN}. At 12 GHz the sun can be approximated as a disc subtending 0.81° and having a brightness temperature of 1.5×10^4 K. For antennas having a beamwidth less than 0.81° then $t_{\mathrm{SUN}} = 1.5 \times 10^4$ K, otherwise, as is the case for the DBS antennas under consideration here, t_{SUN} can be approximated as the appropriate fraction of that value to allow for the incomplete filling of the antenna beam, using the formula $t_{\mathrm{SUN}} \approx 0.19 g_r$. The resulting degradation of *G/T*, and hence *C/N*, can then be calculated for a particular system using the formula given in Section 3.1.2. Typically, the worst degradation for a small DBS installation would be about 3 dB.

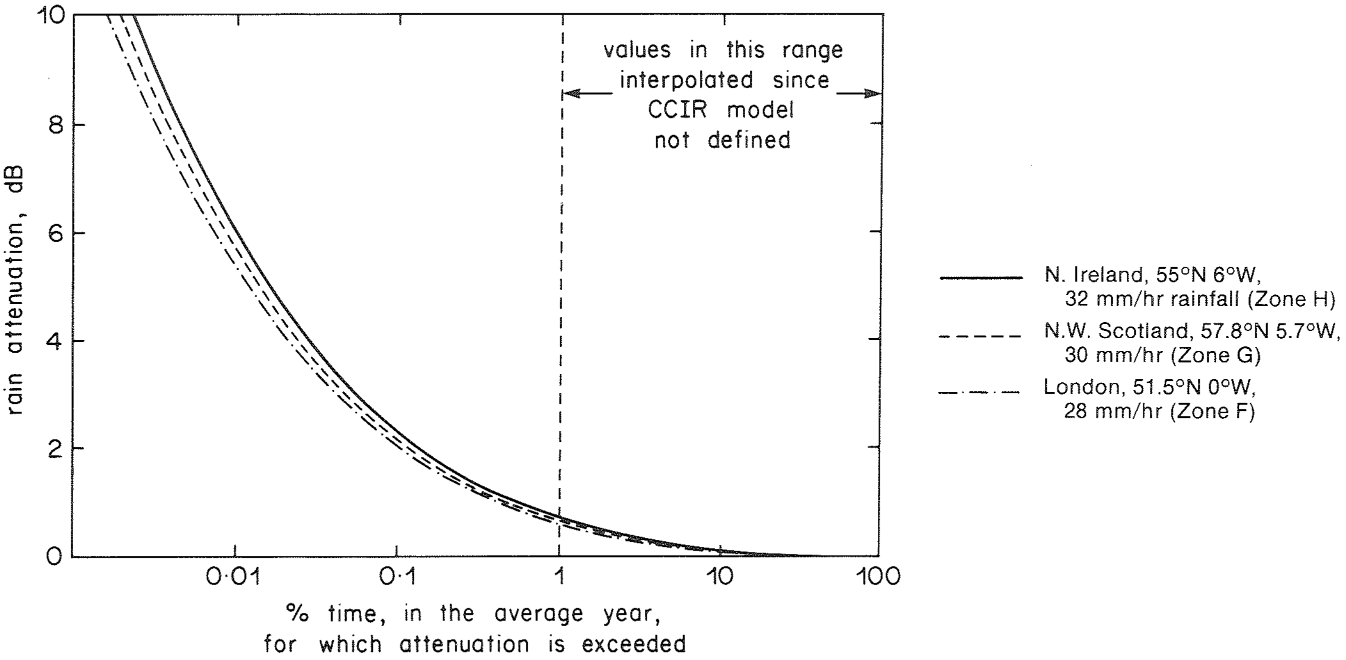

Fig. 2 - The attenuation caused at 12 GHz by hydrometeors on slant paths to three locations in the UK, according to the CCIR model of Reports 564-3 and 563-3.

In practice the signal is attenuated by the atmosphere, and the effect of this can be estimated by treating the atmosphere as if it is an attenuator at an *equivalent medium temperature*, say T_{MEDIUM}. An *equivalent* temperature is used for two reasons:

(a) the actual medium temperature will vary with height;

and (b) because the attenuation mechanism involves both scattering and absorption the equivalent temperature is lower than the actual temperature.

The Appendix shows how the noise temperature of a quasi-ideal antenna having a real radiation pattern but no losses can be estimated as a function of the atmospheric attenuation. The feed losses of a practical antenna can then be accounted for in the usual way as if they are caused by a hypothetical attenuator at the physical temperature of the feed system. Finally, to calculate the overall noise temperature t_{SYSTEM} of the receiving-system the noise caused by the receiver (primarily its front end) must be included as explained in Section 3.1. Fig. 3 shows the equivalent block diagram of the receiver.

Fig. 4 summarises the results of the above calculations, showing how the various temperatures discussed above vary as a function of the atmospheric attenuation, under the following assumptions:

Cosmic background noise temperature	3 K
Equivalent medium noise temperature*	290 K
Ground noise temperature	290 K
Factor accounting for the proportion of antenna noise power contributed by the ground†	0.15
Feed losses	0.5 dB
(assumed to take place at	290 K)
Front-end noise figure	2 to 10 dB as shown.

The effect of atmospheric attenuation can be seen to be most significant for systems where the noise contributions from feed losses and the front end have been minimised. It means that for systems which are required to give high availability, i.e. to function satisfactorily in the presence of high levels of attenuation, it is better to achieve a high G/T by concentrating on improving the gain G rather than trying to minimise the noise figure, since, for systems with a very low noise figure, T is dominated by the effects of the atmosphere when the attenuation is high, which is when a good G/T is most needed.

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* This value is taken for simplicity as a worse case, although, as noted, the true value may be less, depending on the detail of the underlying attenuation mechanism involved. The error introduced is small compared with that from other assumptions. In general, absorption predominates over scattering as the mechanism for hydrometeor attenuation below 30 GHz.

† This is arrived at by integrating the three-dimensional radiation pattern used for the WARC-77 Plan, as explained in the Appendix. The main lobe and nearby sidelobes, which may be assumed to 'look' at the sky, including any noise contributed by attenuation, account for 0.7 of the power response of the radiation pattern when isotropically illuminated. Of the remainder, one-half may be considered to 'see' the sky, and the other half, the ground. The radiation pattern of a real antenna will exhibit many detail variations compared with this idealised example.

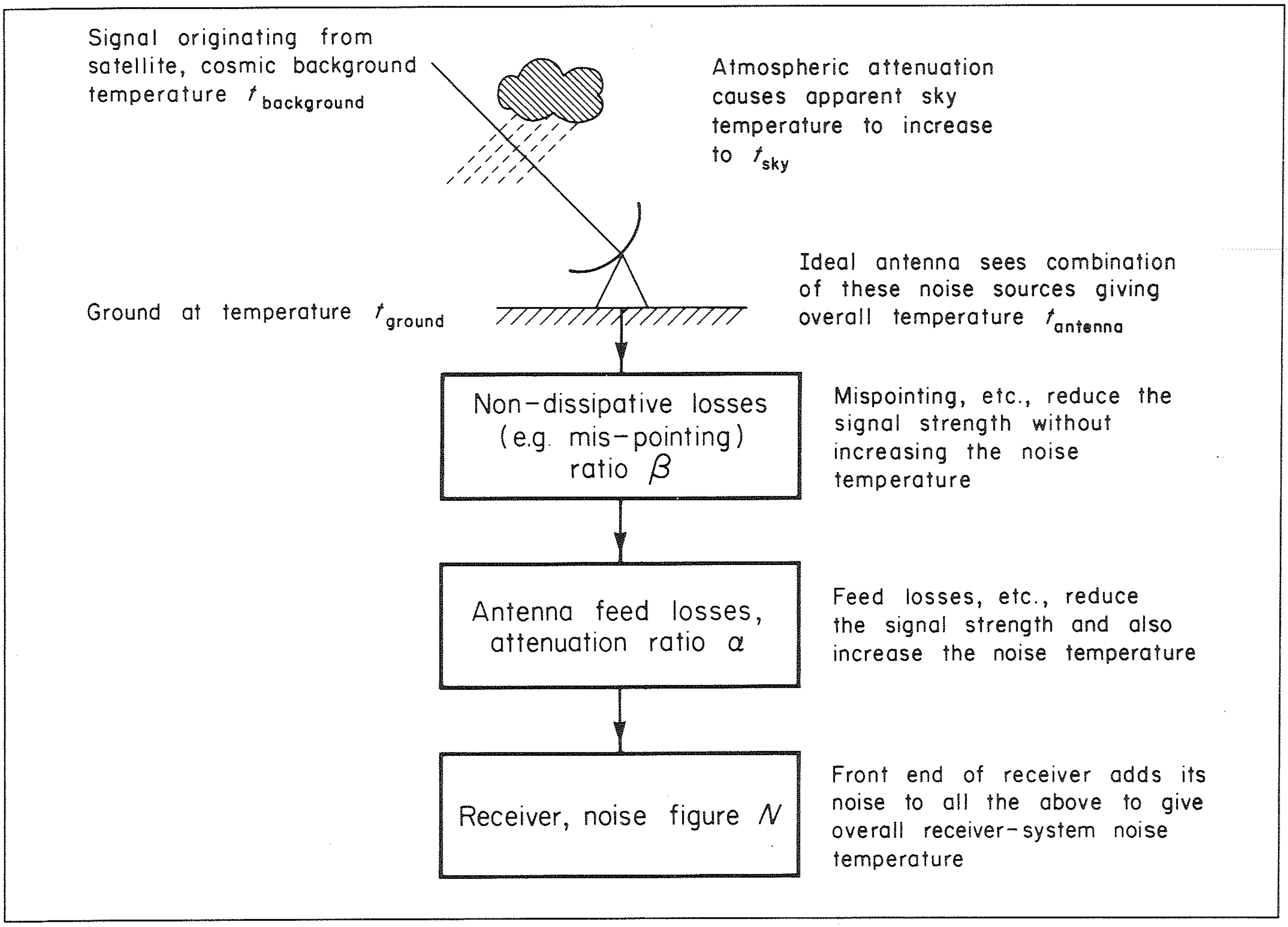
Signal originating from satellite, cosmic background temperature $t_{background}$
Atmospheric attenuation causes apparent sky temperature to increase to t_{sky}
Ground at temperature t_{ground}
Ideal antenna sees combination of these noise sources giving overall temperature $t_{antenna}$
Non-dissipative losses (e.g. mis-pointing) ratio β
Mispointing, etc., reduce the signal strength without increasing the noise temperature
Antenna feed losses, attenuation ratio α
Feed losses, etc., reduce the signal strength and also increase the noise temperature
Receiver, noise figure N
Front end of receiver adds its noise to all the above to give overall receiver-system noise temperature

Fig. 3 - Block diagram of the receive-system including the effects of sky temperature.

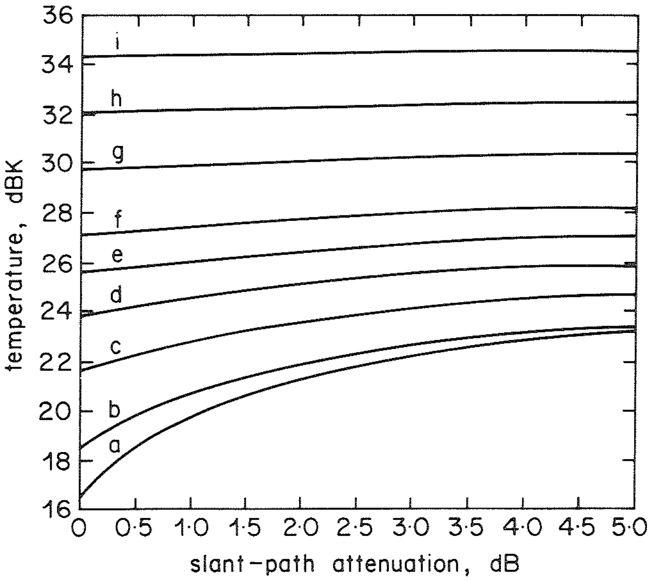

Fig. 4 - Variation of noise-temperature contributions as a function of the slant-path attenuation.

(a) temperature of ideal lossless antenna;

(b) temperature of practical antenna with 0.5 dB feed loss;

(c) to (i), total receive-system temperature for the antenna of (b) coupled with a receiver having noise figures N as follows:

(c) N = 1 dB
(d) N = 2 dB
(e) N = 3 dB
(f) N = 4 dB
(g) N = 6 dB
(h) N = 8 dB
(i) N = 10 dB

3.3 Some examples

Before discussing link-budget examples we must consider what value of *C/N* is needed in order to put the results into perspective. The target minimum value used in drawing up the WARC-77 Plan[3] was 14 dB *C/N* (measured in a 27 MHz bandwidth), to be exceeded for all but 1% of the worst month. This target corresponds to a quality of CCIR Grade 3.5 (see Table 1) for conventional (e.g. PAL) television signals, using frequency modulation[8b]. This is not the very highest quality, but was set as a minimum target to be reached using receivers of modest performance so that cheap receivers could be used. It was realised that better receivers could be envisaged which would then give quality better than the modest target, an option which the viewer could exercise if desired. A *C/N* of 20 dB would correspond to a picture which is of good to excellent quality.

Table 1
CCIR Five-grade Quality Scale

5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

Reception of progressively noisier pictures is possible as the *C/N* is reduced until the *receiver threshold* is reached. This is the value of *C/N* below which noise grossly disturbs the demodulation process so that the demodulated signal has significant artefacts added to it as well as noise. The artefacts typically take the appearance of black or white streaks or dots. The *C/N* at which these effects occur depends on the type of demodulator; for a conventional demodulator the threshold *C/N* is typically 10 to 11 dB, while so-called *threshold-extension* demodulators can reduce this to as low as 7 or 8 dB. Of course, while these techniques can delay the onset of gross disturbances as the *C/N* is reduced, they cannot avoid the fundamental reduction of the video signal-to-noise ratio.

For comparison, the picture quality potentially available to the UK population from the BBC terrestrial UHF TV broadcast network, *taking into account both noise and interference*, is estimated as follows:

Quality ≥ CCIR Grade 4.5 is available to about 88% of the population, while
Quality ≥ CCIR Grade 3.5 is available to about 99% of the population.

These results apply assuming a receiving installation of relatively modest performance*. In many cases a worthwhile improvement is possible by installing a high-gain antenna with a low-noise masthead pre-amplifier; such an installation is likely to be cheaper than any DBS antenna/down-converter combination.

Some examples of link-budget calculations are given in Table 2. It presents calculations for a satellite located at the position allocated by WARC-77 for the UK, with reception in the UK, for four different scenarios A to D. In each case both clear-sky and rain-faded conditions are considered. Rain attenuation of 2 dB has been taken as an example of the rain-faded case; this would be exceeded for about 0.1% of the average year (nearly 9 hours total per year). Case 'A' presents the calculation assuming an EIRP equal to the WARC edge-of-coverage case, with a receiver of similar performance to that assumed in planning. 'B' assumes the same signal is being received using a smaller antenna with a receiver of somewhat higher performance. 'C' and 'D' assume that the signal transmitted is of lower power: one-half of the WARC power for 'C', and a value representative of the current generation of higher-powered *communications* satellites† (e.g. *ASTRA*) for 'D'. These last two examples also assume high performance receivers with dishes of reduced sizes.

Table 2 is given so that the details of the calculation can be consulted. The results may however be judged more clearly from the graph of Fig. 5, in which the variation of *C/N* is plotted as a function of the % time for the four example cases A to D presented in the Table.

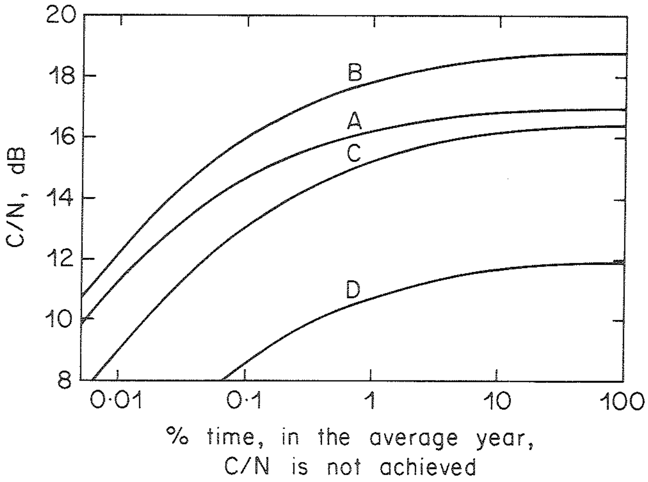

Fig. 5 - The % time (in the average year) for which the given carrier-to-noise ratio (C/N) is not attained, for the four cases A to D specified in Table 2.

The difference between clear-sky and rain-faded *C/N* can be seen to increase as the receiver performance is improved from Case A through B and C to D. Comparison with the modest *C/N* target of 14 dB chosen by WARC-77 shows that Cases A and B, and to a lesser extent C, achieve reasonable performance. Nonetheless, the comparison made at the

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* Analysis assumes a feeder loss of 3 dB together with, for Band IV, an antenna gain of 9 dBd with a noise figure of 8 dB, and for Band V an antenna gain of 11 dBd with a noise figure of 10 dB. The derivation of the relationship between signal strength and picture quality is discussed fully in Refs. 13 and 14, while the population coverage is that currently estimated by Service Planning Section of BBC Research Department.

† Such satellites operate within the frequency band 10.7–11.7 GHz which is allocated to the Fixed-Satellite Service. The value of 11.7 GHz used in these calculations can thus stand as a suitable example for both FSS and BSS bands. A wide range of deviations, and hence suitable receiver bandwidths, is used in FSS applications; nevertheless, the 27 MHz value for noise bandwidth is not untypical.

Table 2: Link Budget Examples

Common features:	
Frequency, GHz	11.7
Noise Bandwidth, MHz	27
Satellite longitude, °E	−31.0
Receiver longitude, °E	0.0
Receiver latitude, °N	51.5
Elevation, °	24
Azimuth, °	218
Range, km	39134
Spreading loss, dB	162.8

EXAMPLE CASES	**A**	**B**	**C**	**D**
Receiver performance:				
Receiving-aperture efficiency, %	**55**	**65**	**65**	**65**
Receiving-antenna diameter, m	**0.90**	**0.60**	**0.45**	**0.60**
whence gain, dBi	38.3	35.5	33.0	35.5
approximate beamwidth, °	2.0	2.8	3.8	2.8
Clear-sky atmospheric loss, dB	0.2	0.2	0.2	0.2
whence clear-sky antenna temp., K	57	57	57	57
Rain-faded atmospheric loss, dB*	2.0	2.0	2.0	2.0
whence (faded) antenna temp., K	136	136	136	136
Dissipative losses, dB	0.5	0.5	0.5	0.5
Non-dissipative losses, dB	**1.5**	**1.0**	**0.5**	**0.5**
Receiver noise figure, dB	**6.0**	**3.0**	**1.5**	**1.5**
whence receiver noise temp., K	865	289	120	120
Clear-sky total system noise temp., K	947	371	202	202
Clear-sky net G/T, dB/K	6.5	8.3	8.9	11.4
Faded total system noise temp., K	1017	441	272	272
Net (faded) G/T, dB/K	6.2	7.5	7.6	10.1
Link budgets:				
Satellite EIRP towards receiver, dBW	**62.0**	**62.0**	**59.0**	**52.0**
Spreading loss (from above), dBm^2	162.8	162.8	162.8	162.8
Area of isotropic antenna, dBm^2	−42.8	−42.8	−42.8	−42.8
Noise bandwidth (from above), dB Hz	74.3	74.3	74.3	74.3
Boltzmann constant	−228.6	−228.6	−228.6	−228.6
Clear-sky atm. loss (from above), dB	0.2	0.2	0.2	0.2
Clear-sky net G/T (from above), dB/K	6.5	8.3	8.9	11.4
whence **clear-sky** C/N, dB	**16.9**	**18.7**	**16.3**	**11.8**
Rain-faded atm. loss (from above), dB	2.0	2.0	2.0	2.0
(Faded) net G/T (from above), dB/K	6.2	7.5	7.6	10.1
whence **faded** C/N, dB	**14.8**	**16.1**	**13.2**	**8.7**

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* This would be exceeded for about 0.1% of the average year at this location.

beginning of this section with terrestrial broadcasting should be remembered. Most of the UK is served by the terrestrial UHF network sufficiently well that in general only a very good DBS installation receiving a high power transmission (e.g. Case B of our example) is likely to match or exceed the performance already achievable terrestrially.

4. INTERFERENCE

4.1 General principles

The primary concern in this section is the mutual interference which may arise between different DBS services, although it should be noted that the 12 GHz band is also allocated to other services having the potential to interfere with DBS reception*.

A degree of mutual interference is inevitable given that the spectrum available for broadcasting is limited. Indeed an arrangement with no mutual interference would make inefficient, wasteful use of the radio-frequency spectrum. The important first step is therefore to identify a *tolerable level of interference.* This is normally expressed as a *protection ratio*, which is the level of carrier-to-interference ratio (C/I) which must be equalled or exceeded to ensure satisfactory performance. The value of the protection ratio will depend on:

(a) the nature of the wanted signal, and its modulation type;

(b) the nature of the potentially-interfering signal, and its modulation type;

(c) the frequency relationship between the signals, together with the performance of the receiver with respect to filtering;

and (d) the proportion of the time for which the interference is likely to be suffered.

When considering mutual interference between broadcast signals we may suppose that they are all of similar type. In the case of the Regions 1 & 3 Plan, this was taken to be "a video signal with an associated carrier, frequency-modulated by a sound signal, both frequency-modulating a carrier in the 12 GHz band" using a specified pre-emphasis characteristic. Other types of signal are permitted to the extent that they cause no greater interference (and would have to be able to tolerate the same degree of interference). In practice all the new systems being considered appear to meet this requirement.

The Plans are channelised; in the case of the Regions 1 & 3 Plan the channels have a spacing of 19.18 MHz and a nominal bandwidth of 27 MHz (i.e. the channels overlap). In this case, mutual interference need only be assessed at integral multiples of the 19.18 MHz channel spacing. Protection ratios are therefore given for *co-channel interference* (CCI) and *adjacent-channel interference* (ACI). (Interference from the second-adjacent channel was neglected in this Plan, although it was taken into account in the Region 2 Plan.) The corresponding protection ratios (for interference arising on the downlink) were taken as 31 dB and 15 dB respectively†.

Mutual interference between DBS services is essentially a function of geometry together with the transmitter and receiver parameters. It will therefore be virtually constant in amplitude for a given collection of services. The protection ratios are therefore chosen as those defining a level of interference which can be accepted *continuously* (and which, in the case of the WARC-77 Plan, causes an impairment corresponding to CCIR Grade 4.5). Atmospheric depolarisation is one exception to this rule; it can cause the level of interference from a cross-polar signal to increase for a small percentage of time — appropriate account was taken of this in the planning process.

It should be remembered that a plan such as that of WARC-77 which appears to guarantee adequate freedom from interference only does so to the extent that the assumptions made during planning remain valid. The effect of changing the receiving installation — and in particular the antenna — is the subject of the next section; the effect of changing the satellite transmitter must also be considered. Any departure from planned characteristics which caused greater interference to another DBS service would not be permissible unless agreed to by affected parties under the rules of the Plan. On the other hand, to operate with a transmitter power less than the plan specified would be permitted, since no additional interference would be caused to others. However, the interference which this service would itself suffer from other DBS services would then, in effect, be increased *pro rata.*

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* The Table of Frequency Allocations (Article 8 of the Radio Regulations) shows that the 12 GHz bands (whose detailed extent is different in the three ITU Regions) are in addition allocated to the terrestrial Fixed and Broadcasting services on a primary basis and also to the Mobile service (primary in Regions 2 and 3, and secondary in Region 1). Footnotes 838 and 844 stipulate that these services shall not cause interference to Broadcasting-satellite services operating in accordance with the relevant Plan.

† The Plan for Region 2 used a channel spacing of 14.58 MHz, and applied CCI, ACI and 2nd-ACI protection ratios of 28, 13.6 and −9.9 dB respectively. (In this case these ratios are applied to the overall carrier-to-interference ratios which include the effects of both feeder links and downlinks).

4.2 The influence of the receiving antenna

The co- and cross-polar radiation patterns of the receiving antenna are the characteristics which determine its part in combating interference. The significance of any departure from the hypothetical patterns assumed in the planning process will depend on:

(a) the receiver location;

(b) the extent to which all the channel/polarisation 'slots' in the corresponding orbit location and its neighbours have been allocated in planning;

and (c) the number of allocations which are actually in use, or can be expected to be implemented later.

Smooth, circularly-symmetrical templates were assumed for the radiation patterns used in planning so that the effect of interference reaching the receiver from any direction could be assessed. This was necessary since part of the planning process was to determine the most appropriate orbit spacing. However, once a plan has been settled (in the case of WARC-77 having 6° spacing between satellite positions*) mutual interference can only come from certain directions.

If we neglect for the moment interference from non-DBS sources, we can see that the antenna need not comply fully with the template used in planning. There is no need to provide discrimination against signals arriving from directions at which no DBS satellites will be situated. These include the 'gaps' between planned orbital locations and also directions away from the visible arc of the geostationary orbit. Furthermore, if the antenna provides sufficient discrimination against the particular most-significant interferers for reception at any location, the performance in the direction of other interferers may be of little importance. In the short term it may also be possible to neglect those allocations which are not expected to be taken up for some time.

Interference from terrestrial sources may impose stricter requirements than other DBS services. In principle, the WARC template should always be adequate for reception within the service area, as far as interference from services sharing the band is concerned, because of the terms of the Plan and the Table of Frequency Allocations (Article 8 of the Radio Regulations). However, other forms of interference, for example harmonic radiation from microwave ovens, may not be so straightforwardly regulated. Careful siting of the antenna may then be highly valuable, since the effects of any type of interference of terrestrial origin may be reduced if the source is screened by buildings and other obstructions.

4.3 Atmospheric effects

Atmospheric effects include both attenuation (see Section 3.2) and depolarisation. Attenuation will not affect interference very much. The most significant interference will generally come from orbit locations close to that of the wanted satellite, so that the slant paths to the wanted satellite and any potential interferer are likely to pass through the same storm cell. The wanted and interfering signals will thus suffer similar attenuation so that C/I is not significantly altered.

Conversely, the effects of depolarisation can be significant. Both hands of polarisation are used in making a DBS plan in order to make effective use of the spectrum. This relies mainly on the cross-polar discrimination of the transmitting and receiving antennas, supplemented by a measure of orbital or geographical separation of service areas served at the same frequency. However, under certain circumstances a measure of depolarisation — and hence introduction of crosstalk between signals of opposite hands of polarisation — is introduced by the atmosphere.

Atmospheric depolarisation is discussed in CCIR Report 722[15]. One mechanism causing it is the passage of the wave through rainfall, whose raindrops are not truly spherical. In this case depolarisation is associated with simultaneous attenuation. Other forms of hydrometeors also cause depolarisation, notably ice crystals above the melting layer in the atmosphere. In this case depolarisation may be caused without significant accompanying attenuation.

The occurrence of these depolarisation effects thus sets a limit to the degree of cross-polar discrimination which it is worthwhile providing in the receiving antenna. It should of course be noted that interference caused by inadequate cross-polar discrimination in the receiving (or transmitting) antenna will occur *continuously*, whereas interference caused by atmospheric depolarisation only occurs some of the time, in varying degree, and thus can only be assessed on a statistical basis. The WARC-77 Plan was assessed for interference assuming that the level of the depolarised component was −27 dB or −30 dB (depending on the rain-climatic zone) with respect to the co-polar component.

4.4 Some examples

This section illustrates some of the foregoing discussion about interference. Results are presented on

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* Satellites are located at 6° increments from 37°W to 29°E. There is then a discontinuity in the regular arrangement, whereby the location of 34°E is allocated to Iran. The regular spacing resumes from 38°E to 170°E (with 164°E unoccupied). Finally, 160°W is allocated to Oceania.

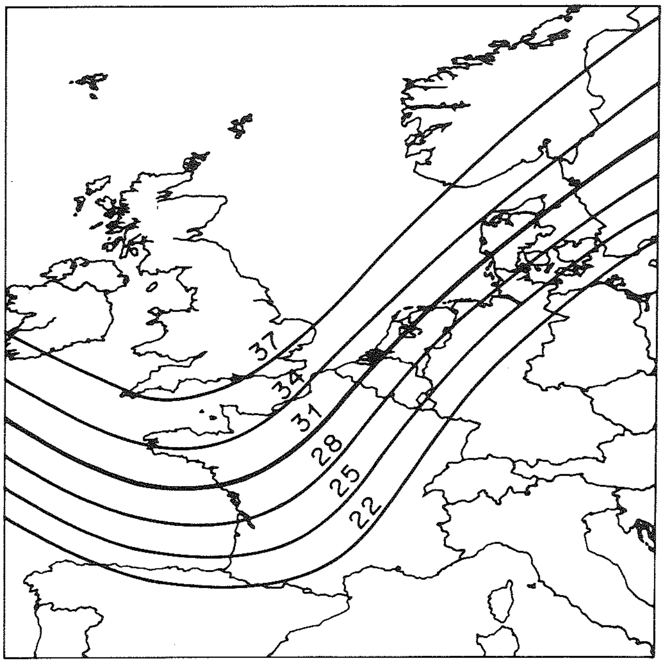

Fig. 6 - Contour plots of C/I in dB for reception of UK DBS transmissions on Channel 4 using a 0.9 m antenna, where the transmissions and receiver conform to WARC-77. Only the beams listed in the main text are considered as sources of interference.

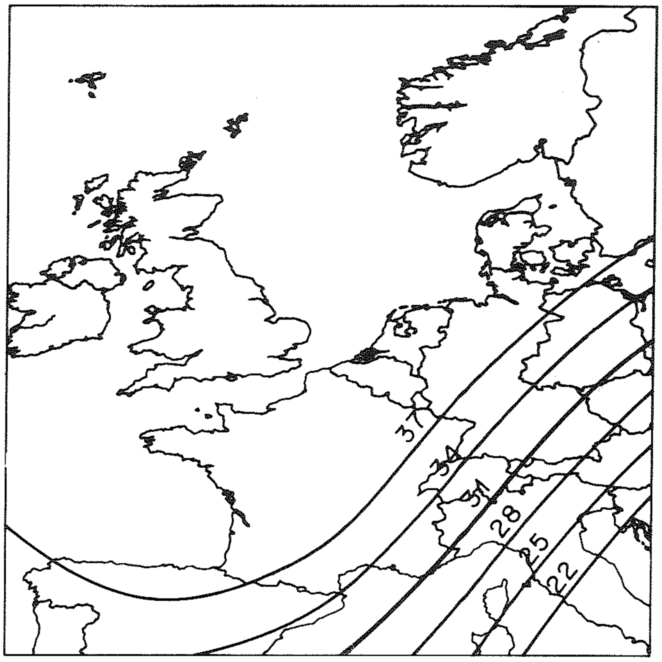

Fig. 7 - Contour plots of C/I in dB for reception of UK DBS transmissions on Channel 4 using a 0.9 m antenna, where the transmissions and receiver conform to WARC-77. Only the French beam is considered as a source of interference.

maps in the form of contour plots of equal carrier-to-total interference ratio for reception of a specific service in the presence of interference from other service(s). The scenario analysed assumes that transmissions are made in accordance with the WARC Plan, but without all the planned transmissions necessarily being active. To calculate the carrier-to-total interference ratio the following procedure is used:

(a) the received power of all interferers on the same channel as the wanted signal is added, giving the carrier-to-co-channel-interference ratio;

(b) the received power of all interferers in the adjacent (upper or lower) channels is added, giving the carrier-to-adjacent-channel-interference ratio;

(c) the results from (a) and (b) are combined by adding the two types of interference powers, but weighting the adjacent-channel interference according to the difference between the protection ratios for co- and adjacent-channel interference, so as to reflect its lesser significance.

The result can be compared with the protection ratio for *co-channel* interference in order to assess how serious the effect of the interference will be. The value used in planning in 1977 was 31 dB*. Thus areas on the map for which the carrier-to-total interference ratio equals or exceeds this value may be deemed to have satisfactory reception, and where the ratio is below this value the quality of reception will be degraded†.

Fig. 6 illustrates the case when using a receiving antenna of the type assumed in 1977 (0.9 m dish, radiation pattern according to the template given) to receive the transmissions intended for the UK on channel 4. It is assumed that most of the transmissions permitted in the Plan which are likely to cause interference are active‡, and that all transmissions are made according to the Plan as regards power and transmitting-antenna pattern. It can be seen that the UK, helped by its geographical location, has been quite fortunate in the way the plan has worked out: all of the UK should receive signals with a *C/I* at least 3 dB better than the planning criterion of 31 dB. For most of the country the result is even better.

Fig. 7 shows a similar case where it is assumed that the transmissions for France are the only source

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* This value of *downlink* protection ratio includes allowances of 0.5 dB for degradation caused by the feeder link and 0.5 dB for degradation from all other services.

† The results obtained during planning in 1977 were presented slightly differently in terms of an *equivalent protection margin* (EPM), essentially the difference between the *C/I* achieved and the corresponding protection ratio.

‡ The beams taken into account in the analysis as potential interferers are the following, using the beam codes specified in the Plan: ALG252 (Algeria), AUT016 (Austria), F093 (France), LBY280 & LBY321 (Libya), LUX114 (Luxembourg), MLI328 (Mali) and ZAI322 (Zaire).

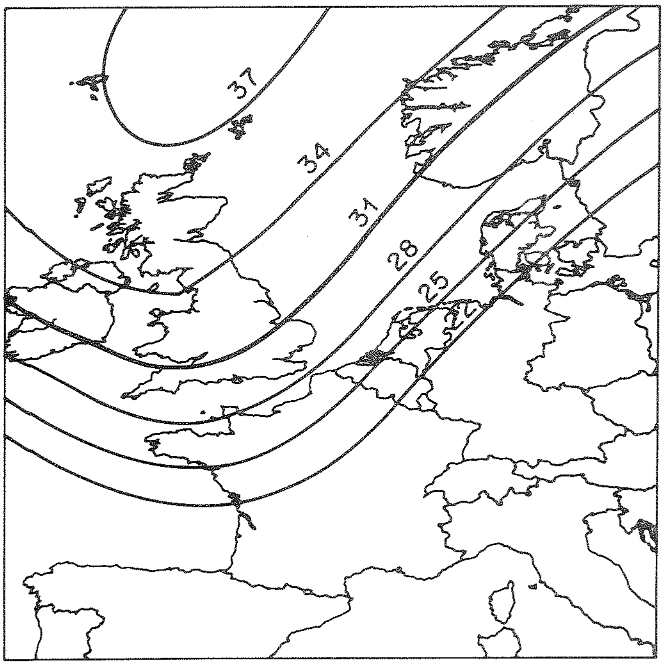

Fig. 8 - Contour plots of C/I in dB for reception using a 0.45 m antenna, whose characteristics are scaled from the 0.9 m WARC antenna. The transmissions and receiver otherwise conform to WARC-77. Only the beams listed in the main text are considered as sources of interference.

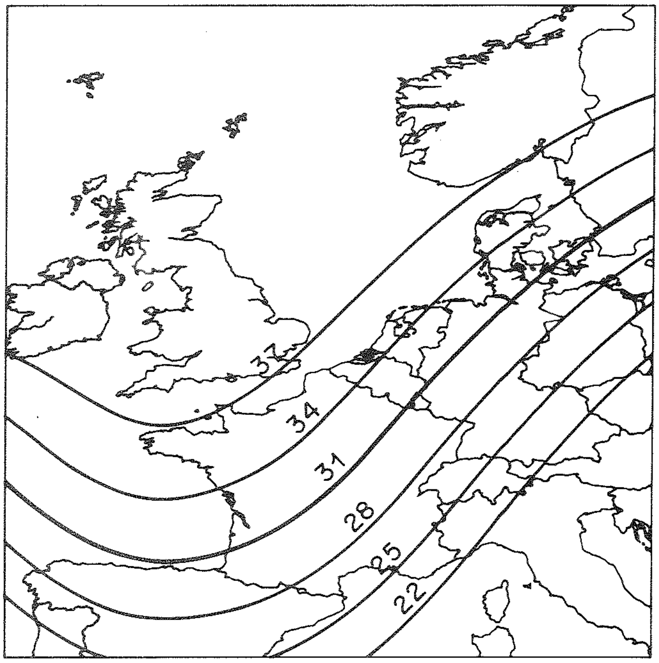

Fig. 9 - Contour plots of C/I in dB for reception using a 0.45 m antenna, whose characteristics are scaled from the 0.9 m WARC antenna. The transmissions and receiver otherwise conform to WARC-77. Only the French beam is considered as a source of interference.

of interference. This is used to illustrate what might arise in the early stages of development when the plan is only partly implemented. The results are still more favourable.

Care should be exercised in interpreting Fig. 6 and 7 for reception *beyond the intended service area.* Fig. 7 would appear to suggest that satisfactory reception of the UK signals (at least as far as *C/I* is concerned) would even be obtained in France, despite the fact that the transmissions to France are the source of interference. This is misleading, and neglects the true nature of the radiation-pattern template which is used to perform the calculation.

The template is not the actual radiation pattern of the transmitting antenna which will be used. Within the main lobe the template is a good approximation to what will be used in practice; beyond the main lobe the template is merely a regulatory convenience indicating the locus which sidelobes must not exceed. Thus calculations of *C/I* performed for reception within the service area are, appropriately, of a worst-case nature: the carrier power is correctly described together with the worst permitted interference. Beyond the service area such calculations are optimistic since the *C/I* is based on a carrier power which relates to the maximum permitted sidelobe radiation rather than the actual value.

The favourable nature of the results presented above suggest that for reception in the UK a receiving antenna having a broader beamwidth or otherwise 'relaxed' specification could be used. As a simple example suppose that the beamwidth is doubled but the same shape of radiation-pattern template is kept. (This might correspond to a dish of 0.45 m diameter otherwise similar to that assumed in 1977). The results are shown in Figs. 8 and 9, where, apart from the change of receiving antenna, the same assumptions apply as previously used in Figs. 6 and 7 respectively. With this small dish, *C/I* would be satisfactory throughout the UK if interference arises from only the French beam, Fig. 9, but with more interferers the quality of reception would be degraded in the south of the UK, Fig. 8. This does not rule out small dishes altogether since designs having lower sidelobes than the assumed scaled template could be devised.

It must be noted that these results assume all transmissions are made according to the WARC Plan. If the UK transmissions were made with reduced power while the interferers retained full power then *C/I* would be degraded dB for dB accordingly. Of course, if all transmissions were made with the same power reduction then *C/I* would be unaffected.

5. REQUIREMENTS FOR DOMESTIC INSTALLATIONS

5.1 Antenna siting

The antenna must be situated so that it has a clear sight-line to the satellite, since no allowance has been made in the link budget for shadowing losses. 'Hard' shadows caused by buildings will definitely obstruct reception while shadowing by trees will in many cases be as serious, particularly when wet. Provided that shadowing is avoided there is no technical reason to seek a high location for the antenna, unlike the case of present UHF terrestrial television broadcasting. Indeed, shielding from possible sources of terrestrial interference would be advantageous. However, it does appear to be sensible to seek a location out of doors.

The main reason to prefer an outdoor location is to avoid loss of signal in passing through a window or roof tiles. Possible mechanisms for loss of signal through windows include:

(a) mismatch (causing reflections at the air/glass interfaces),

(b) absorption within the glass,

and (c) the presence of metal window frames in the near field of the antenna may affect its radiation pattern.

A brief experiment* using sheet glass and a horn antenna showed that losses in the range 1.5 to 4 dB occurred, with some dependence on the angle of incidence of the wave into the glass. In view of the possibility of effect (c) these results should be taken more as a confirmation that losses are possible than as a quantitative indication of what will happen with a practical antenna/window combination. The presence of water, dirt etc., on the surface of the glass must also be considered, although these will also affect the performance of exterior antennas.

Rain, snow, etc., can affect outdoor antennas. In particular, a build-up of wet snow in the bottom of a dish can have a severe defocussing effect. There is thus some advantage in using a dish of offset design such that the dish is mounted in a near-vertical plane while the beam 'looks' upwards towards the satellite at some 20° elevation.

Ref. 16 describes a limited survey which was performed in order to estimate the extent to which the need for a clear sight-line could prove a difficulty. The results suggested that very few potential viewers would be completely deprived of signals, but in some cases, such as the obvious example of north-facing flats, the antenna would have to be mounted in a suitable position elsewhere on the building — possibly as a shared facility feeding a local wired distribution system. An elevated position may be preferred for non-technical reasons: to avoid vandalism, theft or physical hazard from protruding antenna components.

If an indoor antenna were used, it would have to be firmly located so as to remain pointing in the right direction within the small tolerance allowed by the narrow beamwidth.

5.2 Desired facilities

The minimum requirement is for an antenna and associated receiving equipment to receive signals from a specific satellite with carrier-to-noise and carrier-to-interference ratios which are sufficiently great. The antenna beam must be pointed at the desired satellite with sufficient accuracy, and remain so during windy conditions. The antenna should receive the appropriate hand of circular polarisation.

Some viewers may wish to receive signals from more than one satellite (A, B, C . . . say). Where this is possible (under the technical constraints outlined in previous sections) some extra facilities may become desirable. Some examples follow, all assuming that many countries eventually take up their WARC-77[3] allocations.

In some cases nothing extra is needed, e.g. to receive satellites A and B which share the same orbital location, use the same hand of polarisation and have channels in the same half of the frequency band. An example of this situation would be reception of the UK and Eire allocations. In practice it now appears likely that many receivers will cover the whole 800 MHz width of the 12 GHz band, so this will also apply when A and B occupy different parts of the band, e.g. Spain and Portugal.

In other cases A and B share the same orbital position but have opposite hands of polarisation, e.g. France and the Federal Republic of Germany. A minimum requirement is then to provide means of switching the polarisation, whether by physical rotation of the feed or polariser, or by selecting one of two outputs from an orthomode transducer. A further refinement would be to have two front ends so that signals of both polarisations can be taken indoors as two IF feeds. This would permit simultaneous reception of both A and B on two separate receivers in the house.

Similar options arise when A and B occupy different orbital locations. The simplest way to deal with this is to have a single antenna which can be steered mechanically to point at A, B, etc. This is normally accomplished by using a so-called *polar*

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* The author is indebted to his colleague M.C.D. Maddocks for this result.

mount by means of which the antenna pivots about a single axis which is parallel to that of the Earth. An arrangement of this type is used for telescopes in astronomy because rotation about this axis is all that is required to correct exactly for the rotation of the Earth with the passage of time when studying distant celestial bodies. To point an antenna at satellites in geostationary orbit the same axis of rotation is used, with the antenna inclined somewhat towards the Equator (unless the receiving site is itself at the Equator). A small, but not usually significant pointing error then results when accessing a range of orbital locations[17]. Remote actuation of the rotation would be a desirable addition. Only one satellite can be viewed at a time.

More refined antennas can receive signals from more than one direction without the need for physical movement of the main body of the antenna; we may distinguish *steerable* and *multiple-beam* antennas.

Steerable antennas serve the same function as the use of the 'polar mount', i.e. viewing the transmissions from one satellite at a time. Steering may be achieved entirely electronically, as in *phased-array antennas*, or by mechanical movement of the feed of a reflector antenna. (The phased-array principle can also be applied to the feed of a reflector antenna).

Multiple-beam antennas offer multiple outputs, each 'looking' at one satellite. In this case, one receiver could be switched from one output to another to select the desired satellite, or two or more front ends could feed multiple receivers which could each independently and simultaneously select satellites (similar to the dual-polarisation arrangement described above). Polarisation selection might well be necessary as well.

There is thus a wide range of possibilities once the idea of steering or selecting the beam of an antenna is contemplated. One final application of such an antenna is to use its facilities solely to simplify the physical installation even when reception from just one satellite is desired. The antenna is mounted in the most convenient place and its beam steered to the desired satellite. See for example Ref. 4.

6. PRACTICAL EXAMPLES

6.1 Dish antennas

Examples of both link-budget and interference calculations for dish antennas have already been presented in some detail in Sections 3.3. and 4.4. They may be summarised as follows, assuming that reception of 'true' DBS according to the WARC Plan is required:

(a) a 0.9 m antenna

- is the size assumed in planning;
- should fairly readily satisfy the template used in planning, and will thus give satisfactory protection from interference;
- will give satisfactory noise performance with a very modest receiver front end, or considerably improved noise performance (better than the planning target) with a higher-performance but readily-achievable front end;

(b) a 0.45 m antenna

- will require careful design to assure sufficient freedom from interference when most of the Plan transmissions are active, but is probably suitable for reception within the UK;
- will give adequate noise performance provided care is taken to minimise coupling losses, etc., and a low-noise front end is used.

6.2 Flat-plate antennas

The design of flat-plate antennas involves different trade-offs from the design of dish antennas. The objective of course remains the same: to receive a signal sufficiently free of noise and interference.

In principle the efficiency of a flat-plate antenna comprising an array of receiving elements can be high, since the illumination of the 'aperture' can be prescribed simply by the network driving the elements. It is therefore possible to have, say, a uniformly-excited aperture without the spillover which would result if this were attempted using a reflector antenna. However, in practice there will be ohmic losses in both the feed network and the elements themselves. These losses arise both in the copper conductors and the supporting substrate. The conventional solution to this problem, or rather we should say the palliative measure, is to use expensive low-loss materials. This option is not feasible for a mass-produced consumer item so unconventional materials or element structures are of interest. It is also possible to accept some inefficiency provided that it is still possible to deliver pictures of sufficient quality. We have already seen that advances in receiver electronics, particularly in low-noise front ends, permit a significant reduction in the front-end noise temperature so that the G/T requirement can be met with a lower net gain. Of course this cannot be taken too far because of the contribution that the ohmic losses make to the noise temperature.

Similarly, an array antenna can in principle have any desired pattern within the natural physical limits imposed by its dimensions. In practice, especially given the need to minimise losses, relatively simple feed structures are to be preferred so this freedom is much reduced. However, at least for the UK, we have seen that there is some scope for relaxing the WARC radiation template without suffering excessive interference, so this may cause no difficulty.

Related work[4,5,6,7,18] has been carried out to investigate and demonstrate the feasibility of producing a flat-plate antenna incorporating beam-steering so that it can be mounted flat on the most appropriate wall of a house of arbitrary orientation. Until this investigation was completed it was not possible to foresee in detail what could be achieved; nevertheless the above argument showing the latitude available in respect of both noise and interference gave reasonable confidence that flat-plate antennas could provide satisfactory reception.

For example, suppose a flat-plate antenna had the following characteristics:

Aperture size:	Square, 0.75 m × 0.75 m
Aperture efficiency:	95%
Dissipative losses:	4 dB
Non-dissipative losses:	4 dB

and was used at 11.7 GHz with a receiver having a 2 dB noise figure, and in the presence of 1.8 dB slant-path loss. Similar calculations to those performed in Section 3.3 give a faded G/T equal to 6.1 dB/K. This would be just better than the WARC hypothetical receiver and so would give satisfactory results with full-power DBS transmissions. The very high losses are offset by the high aperture efficiency and low-noise receiver front end.

Ref. 4 gives a more detailed breakdown of the losses likely to be incurred in a flat-plate antenna.

7. CONCLUSIONS AND RECOMMENDATIONS

The receiving antenna is a major component in the receiving chain of satellite broadcasting. Its performance, together with that of the associated receiver front end, plays a major rôle in determining the picture and sound quality. Its size, appearance, cost and ease of installation will influence the customer's acceptance of a DBS service.

The hypothetical specification used during the planning of satellite broadcasting, as took place in 1977 for the case of Europe, Africa and Asia, will in general ensure that the planned quality targets are met. However, in particular cases it may be possible to achieve satisfactory performance with a less stringent specification or one in which design trade-offs are differently balanced to achieve a similar end result.

Examples have been presented which show that smaller dish antennas can be used than the 0.9 m diameter assumed for planning in 1977, especially with the lower-noise front ends now known to be feasible.

The possible scope for flat-plate antennas is also indicated. The reader is referred to companion Reports[4,5,6,7] which describe BBC work to make a demonstration example of a flat-plate antenna which is intended to be mounted flat on the most suitable wall of a house of arbitrary orientation.

The work reported here was started in order to explore the development of a demonstration flat-plate antenna. This development will not at present be pursued further since the BBC currently has no direct involvement in DBS. However, there is great interest in High-Definition Television (HDTV), for which satellite broadcasting may well be the preferred method of distribution, perhaps in a different frequency band from the 12 GHz band discussed in this Report. Similar studies of receiving-antenna requirements should therefore be made for the HDTV application.

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APPENDIX

Effect of Slant-path Attenuation on Antenna Noise Temperature*

The slant-path attenuation caused by atmospheric gases and hydrometeors affects the noise temperature of the receiving antenna, t_{ANT}, in much the same way as the more readily-recognised example of an attenuator preceding an amplifier. The effect is well-known and is the basis of the use of *radiometers* to estimate rain-attenuation when a suitable satellite beacon is not available. We must also account for the effect of noise radiated by the ground. To do this it is necessary to take into account the radiation pattern of the antenna — a hypothetical antenna having a narrow beam and no side-lobe responses would clearly not 'see' the ground at all.

Suppose that an antenna is totally immersed in a uniformly 'warm', noisy medium. The total power P received by the antenna within a noise bandwidth B must equal ktB, where k is the Boltzmann constant and t is the noise temperature of the antenna, which in this case will equal the medium temperature. P will be the same irrespective of the antenna radiation pattern, and will be the sum of contributions from all directions. It can therefore be computed as the integral of the product of the effective area of the antenna in a given direction, $a_{\mathrm{EFF}}(\theta,\phi)$, and the power-flux density (PFD) incident from that direction, $p\ \delta\Omega$, over all directions. p here is the PFD per unit solid angle, and for the case of a uniform medium is constant.

$$P = \int_{\text{all }\Omega} a_{\mathrm{EFF}}(\theta, \phi)\, p\, d\Omega, \text{ in general}$$

$$= p \int_{\text{all }\Omega} a_{\mathrm{EFF}}(\theta, \phi)\, d\Omega, \text{ since } p \text{ is constant in this case.}$$

Noting that $a_{\mathrm{EFF}}(\theta, \phi) = g(\theta, \phi) \,.\, \lambda^2/4\pi$, where $g(\theta, \phi)$ is the antenna gain in the direction (θ, ϕ), and $\lambda^2/4\pi$ is the effective area of an isotropic antenna, then:

$$P = (\lambda^2/4\pi) \,.\, p \int_{\text{all }\Omega} g(\theta, \phi)\, d\Omega = (\lambda^2/4\pi) \,.\, p \,.\, 4\pi = \lambda^2 p.$$

Thus the PFD/unit solid angle $p = P/\lambda^2 = kt_{\mathrm{MEDIUM}}\, B/\lambda^2$.

Suppose now that the medium is non-uniform so that a PFD/unit solid angle p_1 is received over a range Ω_1 of solid angle, and another PFD/unit solid angle p_2 is received over the remaining range Ω_2 of solid angle, then the integral becomes:

$$p = \int_{\Omega_1} a_{\mathrm{EFF}}(\theta, \phi)\, p_1\, d\Omega + \int_{\Omega_2} a_{\mathrm{EFF}}(\theta, \phi)\, p_2\, d\Omega, \text{ which may be re-written as before to give:}$$

$$p = p_1 (\lambda^2/4\pi) \int_{\Omega_1} g(\theta, \phi)\, d\Omega + p_2 (\lambda^2/4\pi) \int_{\Omega_2} g(\theta, \phi)\, d\Omega,$$

or in terms of noise temperature:

$$t = t_1 \int_{\Omega_1} g(\theta, \phi)\,/4\pi\, d\Omega + t_2 \int_{\Omega_2} g(\theta, \phi)\,/4\pi\, d\Omega,$$

i.e. $$t = \alpha_1 t_1 + \alpha_2 t_2,$$

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* The author is indebted to his colleague C. Gandy for much of the analysis presented in this Appendix.

where $\alpha_n = \int_{\Omega_n} g(\theta, \phi) / 4\pi \, d\Omega$ and t_1, t_2 are the temperatures of the two media.

Thus the contributions of t_1 and t_2 to the final noise temperature are weighted according to the integrals of the antenna radiation pattern over the solid angles they subtend at the antenna.

The corresponding factors α_n have been estimated for the WARC-77 receiving-antenna pattern, giving the following values:

Mainlobe and nearby sidelobes, factor = 0.7,
other sidelobes, factor = 0.3, split equally between sky-facing and ground-facing components.

We can now estimate the antenna noise temperature t_{ANT}. The mainlobe, nearby sidelobes and one half of the remaining sidelobes will 'see' the sky temperature t_{SKY}, while the other half of the outer sidelobes will 'see' the ground of temperature t_{GND}. Thus the antenna temperature t_{ANT} is given in general by:

$$t_{\mathrm{ANT}} = \alpha_1 t_{\mathrm{SKY}} + \alpha_2 t_{\mathrm{GND}},$$

where $\alpha_1 = 0.85$ and $\alpha_2 = 0.15$ for the WARC-77 antenna.

t_{SKY} in turn comprises t_{B}, the cold-sky cosmic background temperature (about 3 K), reduced by the slant-path attenuation, plus the noise produced by the attenuating medium whose temperature is t_{MEDIUM}. If the slant-path attenuation is $L_{\mathrm{SLANT\text{-}PATH}}$ dB, then writing

$$\alpha_3 = \text{antilog}_{10} \left(-L_{\mathrm{SLANT\text{-}PATH}}/10\right), \text{ in effect a transmission factor,}$$

and applying the usual formula for a dissipative attenuator we obtain:

$$t_{\mathrm{SKY}} = \alpha_3 t_{\mathrm{B}} + (1-\alpha_3)\, t_{\mathrm{MEDIUM}}.$$

t_{MEDIUM} is really an effective temperature and may be less than the physical medium temperature because part of the loss introduced by hydrometeors is caused by scattering rather than absorption. However, scattering is not the dominant process until the frequency is much higher than is the concern of this Report.

We can combine the above equations as follows:

$$\begin{aligned} t_{\mathrm{ANT}} &= \alpha_1 \{ \alpha_3 t_{\mathrm{B}} + (1-\alpha_3)\, t_{\mathrm{MEDIUM}} \} + \alpha_2 t_{\mathrm{GND}} \\ &= \alpha_3 \alpha_1 (t_{\mathrm{B}} - t_{\mathrm{MEDIUM}}) + \alpha_1 t_{\mathrm{MEDIUM}} + \alpha_2 t_{\mathrm{GND}} \\ &= t_1 - \alpha_3 t_2 , \qquad \text{where } t_1 = \alpha_1 t_{\mathrm{MEDIUM}} + \alpha_2 t_{\mathrm{GND}} \\ &\qquad\qquad\quad\;\; \text{and } t_2 = \alpha_1 (t_{\mathrm{MEDIUM}} - t_{\mathrm{B}}) . \end{aligned}$$

There is thus a simple relationship between the antenna temperature and the slant-path attenuation, whatever the radiation pattern and the values we take for the various temperatures. For our example, and assuming that $t_{\mathrm{MEDIUM}} = t_{\mathrm{GND}} = 290$ K, we obtain

$$t_{\mathrm{ANT}} = 290 - 244\, \alpha_3 \text{ Kelvin.}$$

This is plotted in Fig. A.1 in terms of the slant-path attenuation expressed in dB, $L_{\mathrm{SLANT\text{-}PATH}}$.

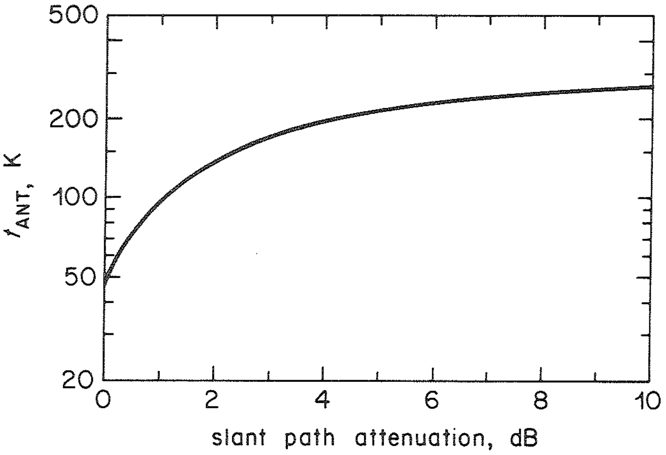

Fig. A.1 - Antenna temperature t_{ANT} *as a function of slant-path attenuation* $L_{\mathrm{SLANT-PATH}}$